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STUDY REPORT,

IMPROVED TECHNIQUES FOR
INTERCONNECTING SOLAR CELLS

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The Sippican Corporation - 1964
Marion, Mass.

CONTENTS

SUMMARY

The Sippican Corporation has completed a study project to determine the feasibility of interconnecting solar cells by welding techniques. This work was performed for the National Aeronautics and Space Administration under contract number NASU-798.

The intent of this investigation was to develop a tough, durable weld between a solar cell and a flexible conductor, with the aim of eventually developing a connection that could be used to fabricate a flexible solar battery assembly.. Our interim Progress Report No. 1, R0248, dated September 6, 1963, describes the selection of materials and the basic configurations suitable for welding with the laser machine.

Fusion welding with a laser beam was the first method evaluated. The laser technique was selected because a temperature hot enough to produce fusion between the materials can be concentrated in a very localized area, a critical requirement for solar cell joining. The first series of experiments, described in the interim progress report, was performed with a laser welder developed at The Sippican Corporation. A comparable series of experiments were later conducted using modified equipment, which lengthened the laser pulse duration. Due to the problems associated with materials and fixturing it is our opinion that laser equipment is not yet sufficiently developed for fully reliable solar cell joining applications.

During the latter stages of the investigation, however, we conducted the joining experiments with a "parallel gap" welding machine. This type of equip-

ment, also known as a "square pulse bonder*," is new to the weld industry. The inherent ability of the equipment to hold the materials while welding eliminates the fixturing problems associated with the laser welder.

We were quite successful with this machine in using gold as an interconnect material. Therefore, it is felt that the potential is high for making a strong, ductile, interconnection capable of being incorporated in a flexible array. Further experiments should be undertaken to explore a full range of interconnect materials, and to thoroughly evaluate this type of weld equipment.

* Tradename - General Electric Co.

1. LASER WELDING EXPERIMENTS

The following sections describe the solar cell interconnection study in terms of cell configuration and types, fixtures, materials and joint configurations.

1.1 Solar Cells

The method of fabrication and subsequent configuration of solar cells are important if welding is to be considered as an interconnection method. The connection pads on the top and bottom of each cell must be of a material that is compatible with a weld process, and the pads must be thick enough to allow welding without endangering the P-N interface. The ideal pad thickness appears to be 0.003 to 0.005 inch. However, since the pads are generally attached to the solar cell by vapor deposition, it is difficult to acquire the desired thickness. This factor weighs heavily against welded interconnections at this time.

The first two types of solar cells evaluated were of silicon P-N 1 x 2 cm and had pads of 0.000040 inch titanium kovar and 0.000040 inch silver. In each case these vapor-deposited pads were found to be too thin; therefore, the same two materials were used to fabricate 0.001 inch pads. The cells used in the experiments were specially fabricated by Texas Instruments. Solder coated cells were also evaluated, but were not satisfactory for this application.

1.2 Fixturing

Because laser welding equipment does not provide a means of exerting pressure on the workpiece, suitable holding fixtures, including miniature vices, spring hold-down clips and pressure probes, were tried. The workpiece holding problem is complicated, however, because most materials, of less than 0.010 inch thickness have a tendency to roll back rather than flow during welding. Therefore, the hold-down device must allow these thin materials to be clamped immediately adjacent to the weld area. One successful approach, a modified forceps which clamps the wire for welding, is shown in the illustrations.

A glass plate (see illustration), placed directly on top of the materials to be welded, was evaluated. We used dummy micrologic elements to test this type of fixture. This method provides sufficient holding pressure and allows the laser beam to penetrate, but the glass is prone to thermal shock. Consequently, it will chip in the area of the weld, leaving glass splinters attached to the metal around the joint.

It appears feasible to modify an objective lens so that there are probes attached directly to it, which allows the lens, when brought into focus, to exert mechanical pressure on the workpiece. This method of jigging is most promising, however, our attempts were hampered by weld gas and metal fragments fogging the lenses. More work needs to be done in order to provide suitable lens shielding methods.

1.3 Interconnecting Material

A solar cell interconnecting material that is suitable for laser welding must have good flow properties in the liquid state. Therefore, materials such as gold, silver, nickel, copper and Kovar were evaluated (see Table 1). Of these, copper was judged unsuitable because experiments showed that it reflected a large percentage of the red light emitted by the ruby rod. Nickel and

Kovar, because of their higher melting points, are more desirable than gold or silver for laser welding. Higher melting point materials do not conduct heat as readily into the silicon substrate, so that as long as the entire interconnect material and pad does not become molten, the heat of fusion will not damage the silicon P-N junction.

In laser welding, the interconnecting material should be at least 0.003 inch thick and, as previously mentioned, the pad to which it is to be joined must be at least 0.003 inch and preferably 0.005 inch thick. It is also desirable to have a flat, nonreflecting surface, such as the lightly etched surface of a smooth material. A nonlusterous finish is more absorptive, while a smooth surface permits good contact between the two pieces to be welded. Examples of such materials are lightly etched, rolled copper or nickel ribbon. Similarly processed silver material cannot be used because etching produces an adherent by-product that interferes with good metallic contact.

Evaporation or "cratering" is a constant problem during laser welding (see illustration). If the spot size of the beam is kept small, the energy density and rate of application are such that a fairly large amount of material is vaporized. Because of the limited output of existing equipment, no melting occurs if energy is lessened by substantially increasing the spot size. Spot sizes range from 0.005 to 0.007 inch diameter up to 0.020 to 0.030 inch diameter. Spot sizes can be controlled to a certain extent by focusing and defocusing, as well as by switching the objectives lens (see illustration).

The obvious solution, therefore, is to modify the basic equipment to allow a more prolonged rate of application, e.g. 3 milliseconds, but with the current state of the art in flashlamp technology, it is difficult to obtain a laser pulse of this length. Practical pulse lengths are in the range of 1 1/2 to 2 milliseconds at the present time. As laser technology is developed, however, this duration should be easily extended to 5 milliseconds and energy bursts of this length should facilitate welding thin sections. The short pulse duration is the second major deterrent to laser welding of flexible interconnections to solar cells.

1.4 Joint Configuration

A joint configuration or "geometry" for laser welding is another problem area. The well known lap weld configuration produces a condition that is too vulnerable to peel load and is, therefore, not good enough for a flexible interconnection. The best type of joint configuration is a form of plug weld. In this joint design, the top piece of material has a drilled hole approximately 0.005 to 0.008 inch in diameter. To use this configuration, however, the material thickness of the solar cell would have to be substantially increased over the recommended 0.005 inch in order to survive the direct energy of the laser beam and protect the P-N interface. These geometries are shown in the illustrations.

Butt weld geometry was also tried and was found to be desirable for joining similar materials where the edges can be placed together; however, this geometry, due to extreme thinness of the P-layer on the solar cell, could not be used because of damage to the interface.

The redundant ribbon to cell interconnection method, shown in the illustrations, would be recommended for production purposes. This basic geometry permits two or more welds to be made to the top and bottom contact surfaces of a cell. As the material adjacent to the weld is consistent a single weld behaves the same as a string of welds. Thus to simplify weld evaluation work, development was limited to single welds to make efficient use of materials on hand.

Table 1 - Power at various magnifications to accomplish melting on silver, copper, gold and nickel.

0.003 inch material

Power Level	Gold			Silver			Copper			Nickel		
Melting Setting	4X	6X	10X	4X	6X	10X	4X	6X	10X	4X	6X	10X
Threshold for L 0(3000v)			M			M			HT		HT	HT
0.033					HT							
0.066												M
0.1			C						M			
0.133				HT		C					M	
0.166		HT										
0.20												C
0.233	HT								C			
0.266					M	HE		HT		HT		
0.30			HE								C	
0.333		M										HE
0.366					C	B						
0.40									HE			
0.433												
0.466											HE	
0.50	M	C			HE		HT	M				B
0.533												
0.566			B						B			
0.60										M		
0.633		HE		M				C				
0.666	C											
0.7												
0.733											B	
0.766	HE	B		C			M			HT		
0.80								HE				
0.833					B							
0.866												
0.900												
0.933							C	B		HE		
0.966	B			HE								
1.000(4200v)												

Legend: C = Cratering B = Blow HT = Heat Tinting* M = Melting
HE = Heavy Evap. * Insufficient energy density for welding

Table 2 - Comparison of Inductance Effect on Pulse Length

Inductance Value	Effective Pulse Duration
0.110 millihenry	0.4 milliseconds
0.335 "	0.6 "
0.585 "	0.7 "
0.975 "	1.0 "
1.18 "	1.2 "
1.48 "	1.4 "
1.8 "	1.7 "
2.15 "	2.0 "

2. PARALLEL GAP WELDING EXPERIMENTS

In the later stages of the solar cell joining experiments, it was evident that the laser machine at its present level of development, was not the ideal equipment for this particular type of interconnection. In the interest of the overall study, The Sippican Corporation decided to use the remaining time and materials to evaluate a parallel gap welding machine that had been obtained from the General Electric Company. This machine, known as a "square pulse bonder" showed considerable facility for making the desired interconnects.

With parallel gap welding, the force provided by the welding electrode is sufficient to hold the materials in contact. Fixtures, therefore, may be limited to devices that merely position the materials prior to making the weld.

A good cell/material combination for parallel gap welding requires an interconnecting lead of 0.002 to 0.003 inch thickness and a deposited pad of 0.001 and 0.002 inch thickness. This configuration presents a minimum of problems to the solar cell manufacturer, and it has been demonstrated that a high degree of consistency and reliability can be obtained (see illustrations). Gold appears to be the ideal material for parallel gap welding because it has sufficient resistivity to allow welding without seriously limiting current carrying capability and possesses excellent post-weld properties.

The only immediately evident drawback appears to be that materials with higher electrical conductivity are nearly impossible to join by parallel gap welding methods, because this type of welding generates the necessary heat through the resistance of the material to the flow of current.

3. EQUIPMENT

3.1 Laser Welder

The Sippican Corporation used a specially designed and constructed laser welding unit for the experimental work. The laser was manufactured by Lear Siegler, Laser Systems Center, and used with specially constructed optics purchased from Bausch and Lomb. The size of the resultant weld is very small, and optics are required for handling and positioning to insure adequate placement of parts. On the laser equipment these optics are part of the beam-focusing mechanism.

The unit is capable of the following:

(a) Laser outputs of 1/4 to 3 joules of energy.

(b) Multiple pulsing at a rate of 1 pulse per 3 seconds for maximum output. Equipment modified to obtain durations up to 2 milliseconds.

(c) Spot sizes from 0.0002 inch to a practical maximum of about 0.030 inch.

Larger spots are optically possible but, in most cases, would not result in any melting of the material due to low energy density.

The unit possesses the following controls (see illustrations).

(a) On/off console power. This switch energizes the panel, turns on the water pump for the closed loop cooling, energizes all the high-voltage electronics, but does not charge any of the high-voltage capacitor bank.

(b) High-voltage standby switch. This control is a standby position for setup work, and can be used to discharge the capacitor bank if the unit has already been charged.

(c) High-voltage switch. This control energizes the capacitor bank. Energizing is at a fixed rate and will reach whatever value is set on the 1 to 10 laser output dial.

(d) Laser output dial. This control allows the capacitor bank charge to be varied from about 3000 to 4000 volts.

(e) Manual/automatic switch. This control allows the operator to select either manual or automatic firing. When in automatic condition, the unit will fire each time the programmer reaches 0. This interval can be varied from 3.5 to 30 milliseconds.

3.2 Parallel Gap Welder

The parallel gap welder or square pulse bonder produces extremely uniform surface bonding of leads to microminiature electronic circuitry. The control system supplies rectangular power pulses to the electrodes. The pulses are controllable and can be adjusted in amplitude, duration and spacing. This allows precise matching of the control output to the power requirements of the material being bonded. The capability of the welder is as follows:

Energy Rating:	40 to 400 watts per pulse
Pulse Duration:	5 milliseconds max. to 0.5 milliseconds min.
Spacing Additions:	1 to 8 milliseconds (minimum spacing is three times pulse duration)
Max. Bonding Rate:	6 to 10 per second (depending on work load)
Number of Pulses:	1 to 20 in 16 steps

Pulse amplitude is infinitely adjustable by the combination of a stepping switch and vernier rheostat, thus allowing positive return to previously established settings for precise repeatability. A capacitor bank assures that successive pulses will be of uniform amplitude at the present levels. Pulse duration can be infinitely varied through the combination of a stepping switch and vernier rheostat. Interpulse spacing can be selected by a stepping switch in eight steps beyond a minimum time proportional to the selected pulse time.

The operator's controls and the display of pulse parameters are conveniently grouped and readily accessible on the front panel. A calibration meter is provided on the console so the proper d-c reference voltage can be easily established.

An electrode continuity and alarm system is provided to indicate an electrode short circuit as well as proper electrode-to-work conductivity. The continuity system locks out the firing circuit unitl proper continuity is achieved. The bonder is equipped with a trip circuit which disconnects the firing circuit automatically if the control capacity is exceeded.

A wire advance and wire retract control system is included for an optional automatic wire feed. A vacuum supply is provided for a vacuum pencil as well as for work-piece holddown. This aids the operator in handling parts without contamination.

4. CONCLUSIONS AND RECOMMENDATIONS

The problems of solar cell welding are twofold: first, developing a geometry and a process for welding the cell to an interconnection and, secondly, the selection of the size, shape and composition of the materials that offer the best weld.

The results of our investigation show that laser welding is not now generally applicable for the production welding of thin materials to solar cells. The basic reasons for this conclusion are as follows:

(a) There is a problem in fixturing to maintain close contact of the materials.

(b) The probability of damage to the P/N interface is too high and cannot be tolerated with present equipment.

(c) Vaporization and cratering present drawbacks that have yet to be overcome.

(d) Vapor and small particles rising from the molten weld can cause lens failure.

The laser process appears to be more adaptable to the welding of plug type geometries; in particular, where a material extends through and slightly above a hole (see illustration). Where this geometry is employed, gravity will allow the molten metal to flow downward and bond to the sides of the hole. When lap weld or butt weld geometries are used, the problems of fixturing, burn and evaporation are too extensive in the materials to provide consistent, reliable joints.

Within the next 18 to 24 months, the advancement of laser technology is certain to overcome the drawbacks which result from too short a pulse, and we believe that the fixturing problems can be worked out. The inherent advantages of laser are namely:

(a) High energy density.

(b) High temperatures.

(c) Approach from single side.

(d) Minute energy area.

(e) External accurate control of energy spot location.

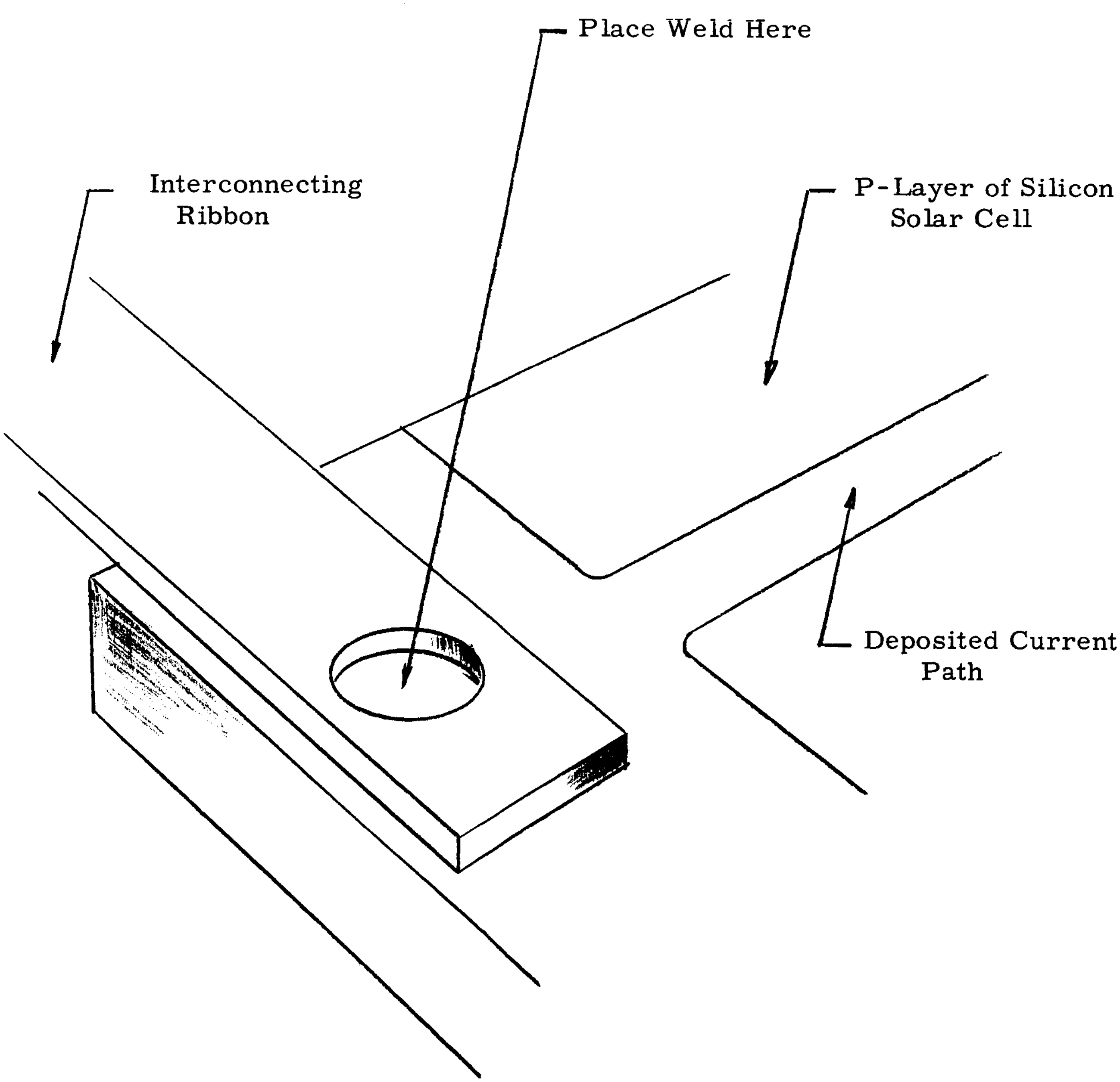
(f) Advantages of electron beam plus better accuracy and no need for vacuum enclosure.

Therefore, despite the appraent multiplicity of problems encountered in laser welding of thin material, the future is good.

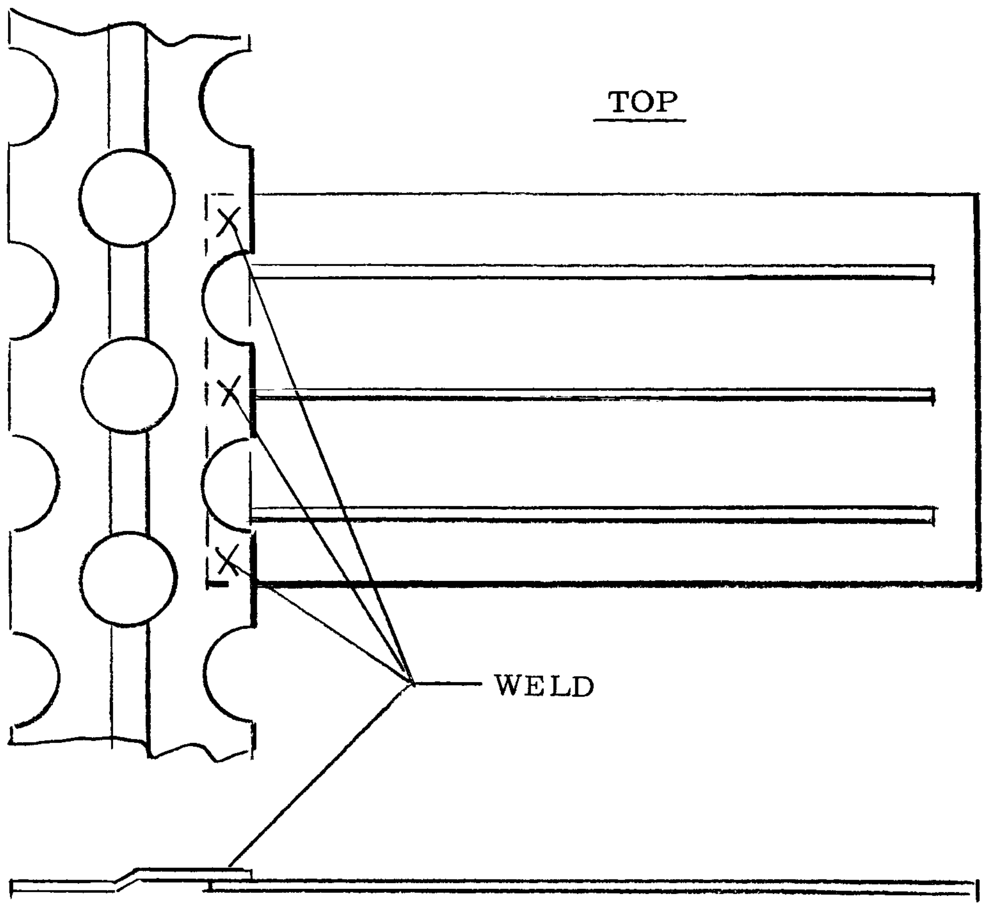
Through the use of the parallel gap welding process, the geometry is well established. What remains to be done is a more thorough search of materials that are usable for this weld process and the evaluation of a trial assembly. Materials chosen primarily for laser welding were used for the subsequent parallel gap experiments; therefore, they are not necessarily the best selections for parallel gap welding.

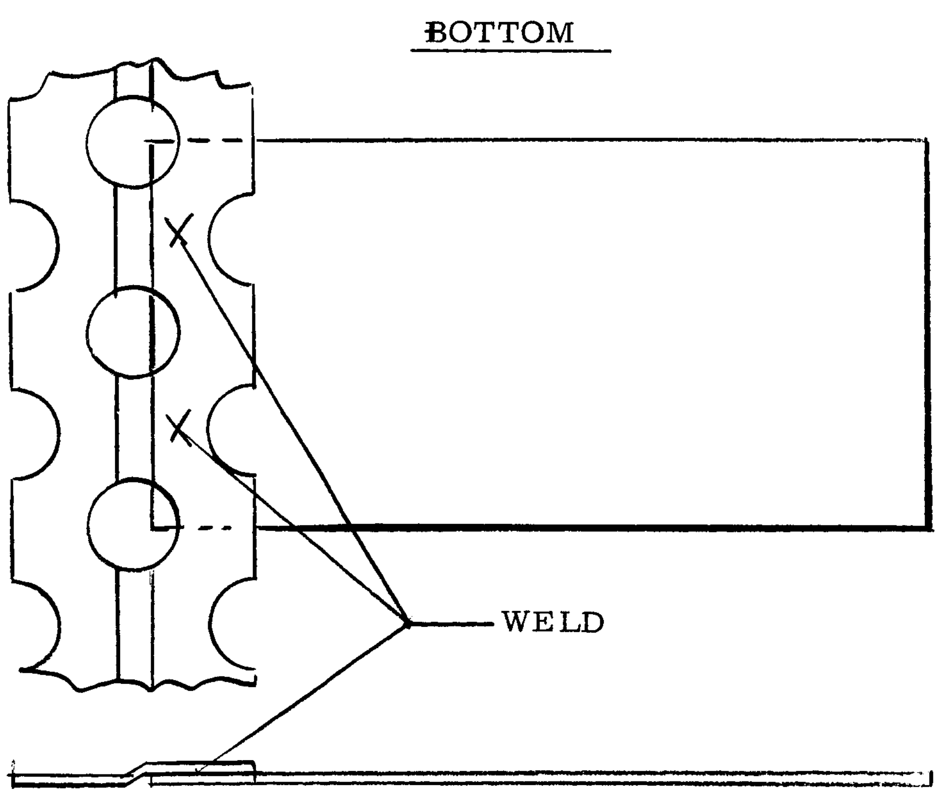
The accompanying macrophotos and photomicrographs illustrate the various connections and techniques that were tried with solar cells and the feasibility of flexible interconnections. Samples submitted are on cells with data previously taken by W. Cherry at Goddard.

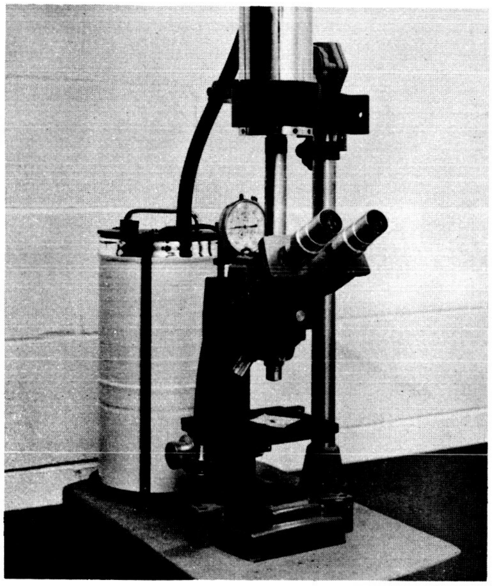
PLUG WELD GEOMETRY FOR LASER WELDING
SOLAR CELL TO RIBBON



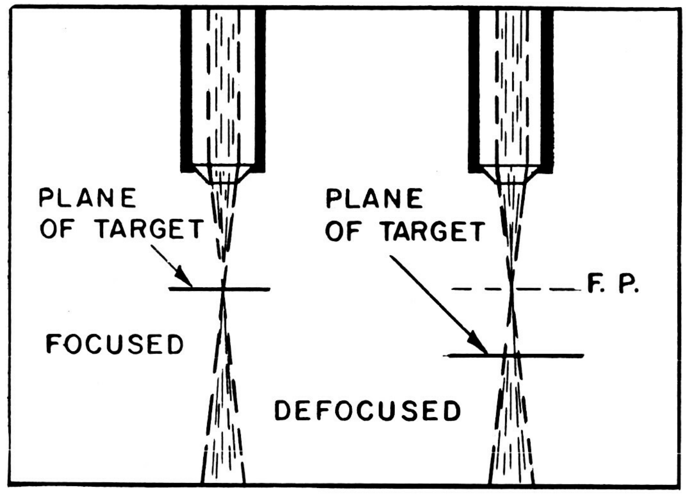
POSITION OF RIBBON ON SOLAR CELL





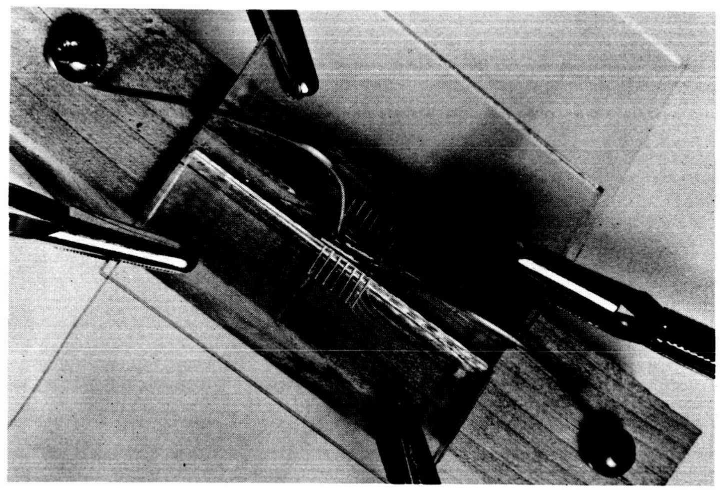


A Laser Weld Head with Stage and Accessory Optics.

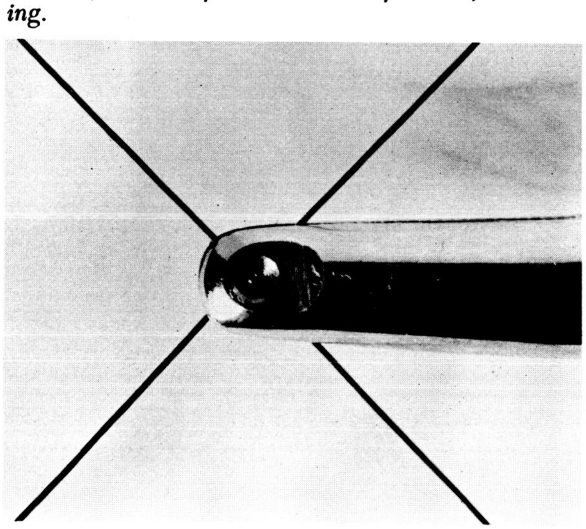


Position of Target with Respect to Laser Beam Showing Use of Defocusing Method to Vary Spot Size.

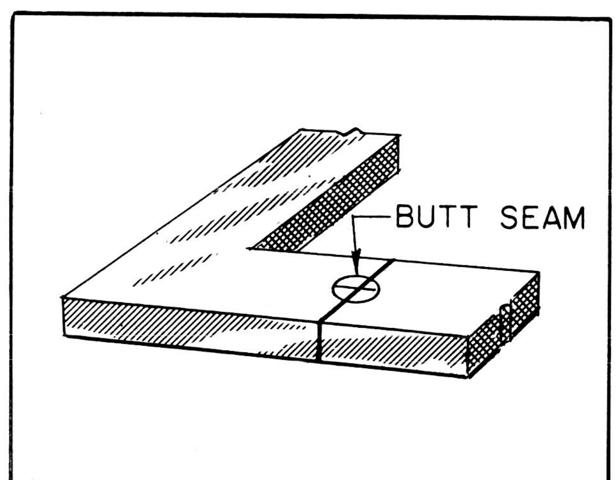
A Micrologic Stick Fixtured using Glass Plates and Clamps to Align Pieces and Maintain Contact.

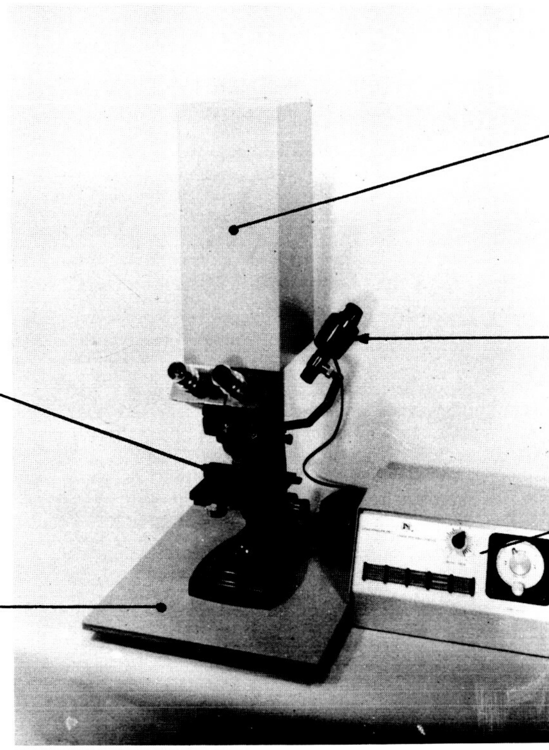


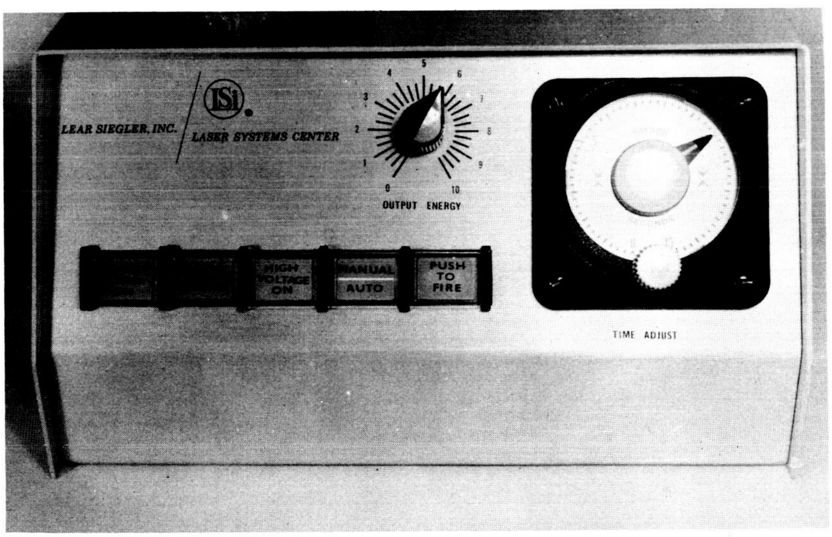
A Modified Forceps used to Clamp Wire for Welding.



The Butt Weld Geometry Showing Optimum Beam Position.

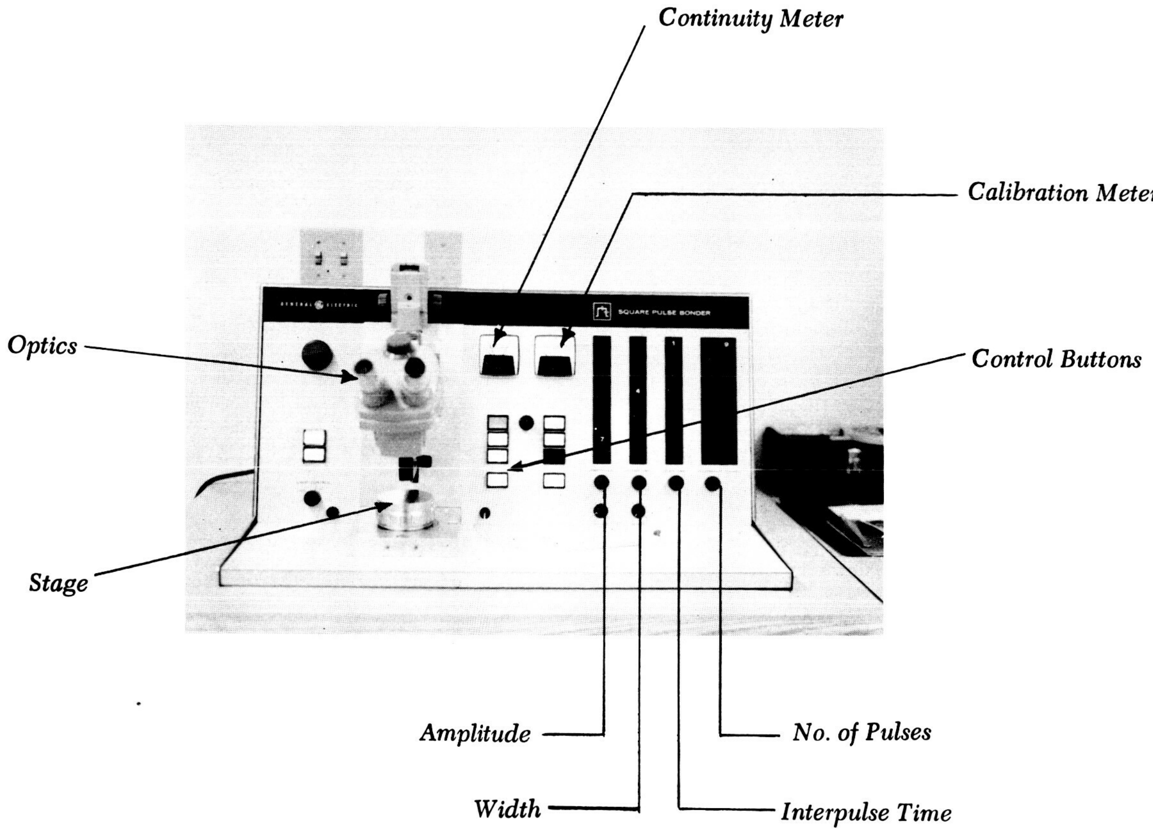


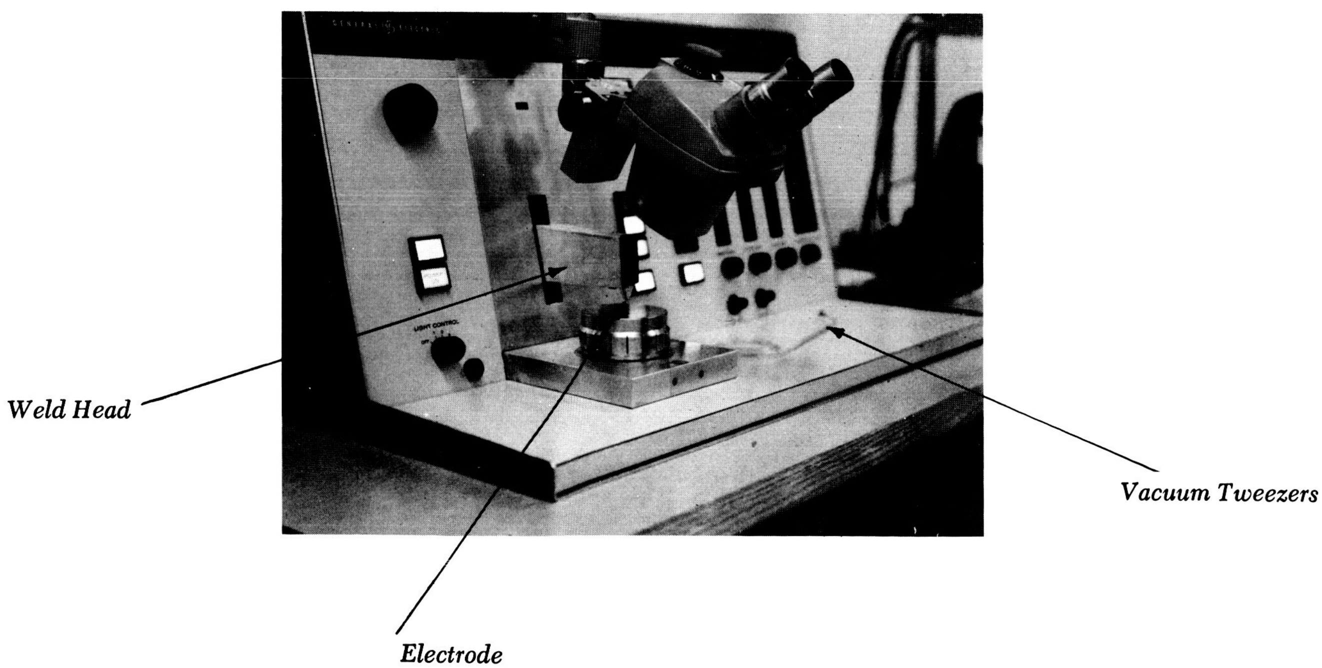




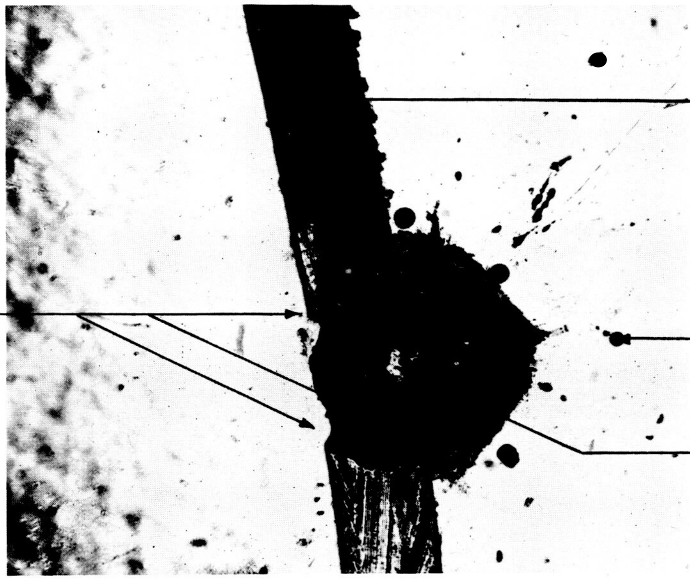
Power Control Console

Laser welding head and control console. Unit is equipped with X-Y-Z axis stage, separate illumination and and tri-objective turret with 4X, 6X, 10X objectives. Pulse duration on this equipment is approximately 2 milliseconds.



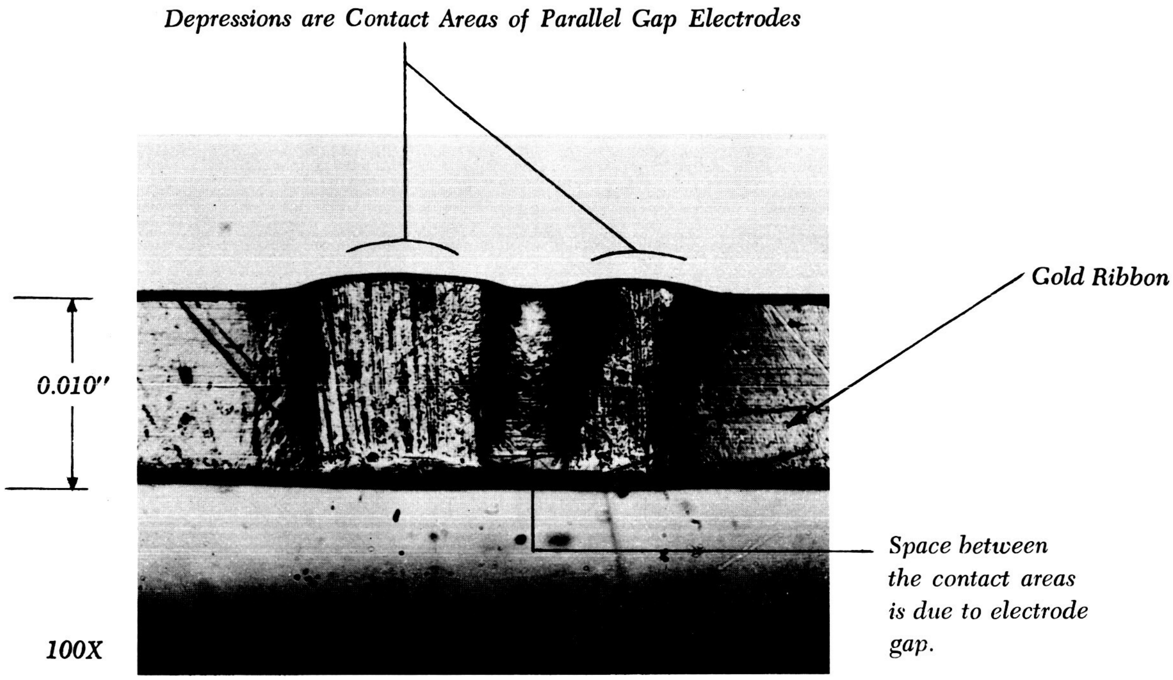


The GE "Square Pulse Bonder" (parallel gap) with stereozoom microscope. The unit has X-Y micro-positioner, vacuum tweezers, continuity circuit and digital readout on all variables; pressure is adjustable and can be varied from 1/2 to 6 lbs.

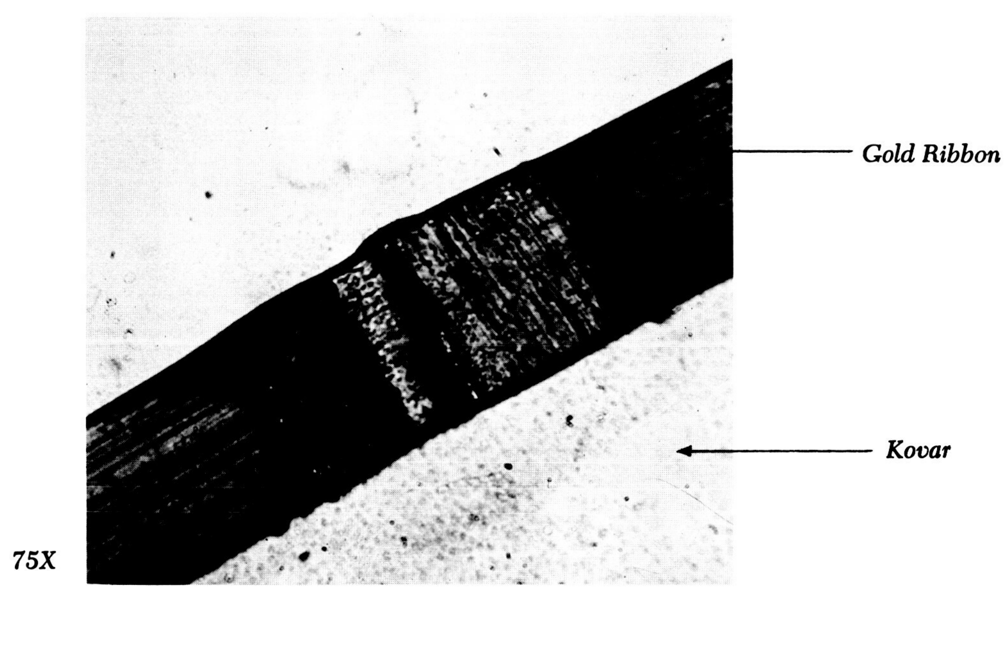


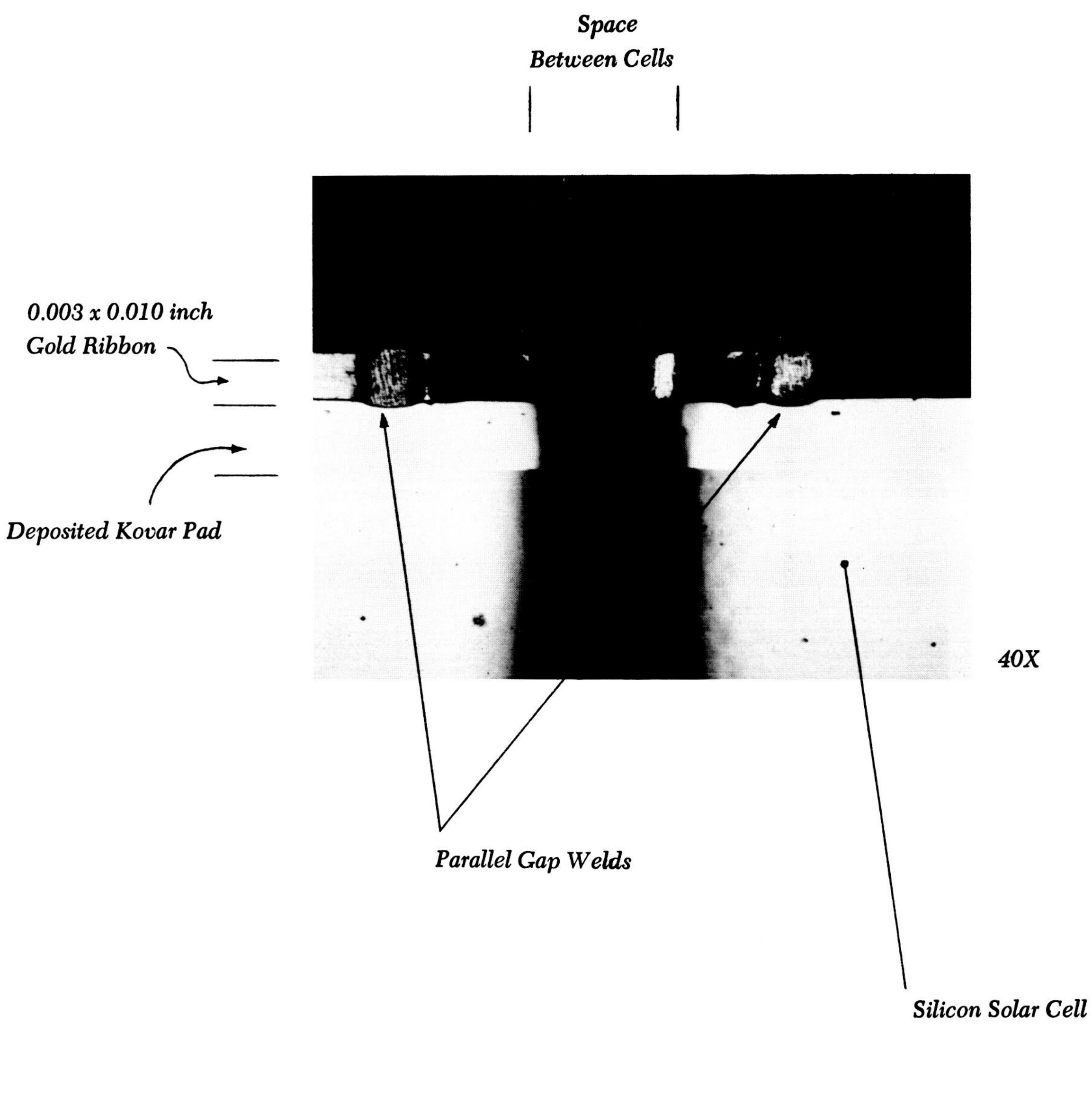
Sample of 0.003 x 0.010 inch gold ribbon laser welded to Kovar pad on silicon solar cell. Note traces of expulsion and signs of cratering. Present pulse durations are generally too short to permit melting without some vaporization and resulting crater formation.

Sample of 0.003 x 0.010 inch gold ribbon both laser and parallel-gap welded. Expulsion and splattering are evident about the laser weld, while the area about the parallel gap weld is undisturbed.



Samples of 0.003 x 0.010 inch gold ribbon parallel-gap welded to Kovar pad on silicon solar cell. Notice, in each case, the two depressions where the electrodes contacted the gold ribbon.





Two solar cells joined by parallel-gap welding. Welds are located where ribbon is swaged.